THE EFFECT OF WORK HARDENING ON THE FATIGUE PROPERTIES OF FERRITIC STAINLESS STEEL AT ELEVATED TEMPERATURE

WILLIAM A. SKINNER

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by

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Submitted in partial fulfillment of
the requirements for the degree of

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ABSTRACT

The purpose of this study was to determine, to what extent the improvement in fatigue strength obtained by cold work is altered by cyclic stresses at elevated temperature.

A series of fatigue tests were conducted using type 430 stainless steel in both the cold worked and the annealed conditions, at temperatures above and below the recrystallization temperature.

PREFACE

The experimental work reported herein was conducted by the author at the United States Naval Postgraduate School, Monterey, California, during the period from February to May of 1958.

The writer wishes to express his appreciation for the assistance and encouragement given him by Professor Alfred Goldberg of the U. S. Naval Postgraduate School in this investigation. The assistance of the technical staff of the Department of Metallurgy and Chemistry in building and setting up the necessary equipment is also noted and greatly appreciated.

1. Introduction.

Recent trends toward the use of higher temperatures in heat engines, high speed aircraft and rockets, make necessary a better understanding of the effects of elevated temperatures on the mechanical properties of materials. In order for designers to meet present day specifications with materials now available, the use of large safety factors is no longer possible, and consideration must be given to all the factors which may influence the materials used.

Although, the problem of fatigue in metals has been studied extensively for over 100 years, it has only been in the last 15 years that the effect of high temperatures on this problem has received much attention. This has been due partially to the assumption that at elevated temperatures, metals will fail due to creep rather than to fatigue. However, most authorities who write on this subject emphasize that this assumption is not universally valid for all metals and all temperatures. (1), (2) Certain phenomena which occur in metals at elevated temperatures are influenced by the presence of alternating stresses; and, therefore, a composition or metallurgical treatment developed to give optimum creep characteristics may not produce favorable fatigue properties.

There have been a number of methods developed for improving the fatigue strength of metals. Most of these have been developed from considerations of room temperature applications only, however, it appears that some may have merit at elevated temperatures also. In most engineering applications, the maximum stress occurs at the surface of the stressed member. Since fatigue failure would most probably, originate in the

region of highest stress, it would seem that strengthening of the surface would improve the fatigue properties of the material. Surface hardening may be accomplished by any one of a number of methods depending on the alloy used. Some methods in common use are carburizing, cyaniding, nitriding, case hardening and strain hardening by cold rolling, shot peening or cold drawing.

It has been shown by a number of investigators, that strain hardening will increase the endurance limit of some metals at room temperature. (3) Moore and Kommers (4) found an increase of 64% in the endurance limit of unnotched rotating beam specimens which had been cold drawn from 0.50 to 0.44 inches in diameter. Their experiments were conducted using mild steel specimens. Oberg and Johnson (5) found an increase of 100% in the stress necessary to cause failure in ten million cycles, when using rotating beam specimens of 18-8 steel which had been cold drawn. In the same paper they reported a decrease of 30% in the fatigue strength of Inconel under the same conditions.

It is evident then, that the fatigue strength of some, but not all, metals may be considerably improved by strain hardening, and it appears that there are enough metals which do show an increase in strength to make this method worthy of consideration.

In considering metals for high temperature applications, it would be of interest to know what changes in this improved fatigue strength would take place at elevated temperature.

Wever (6) states:

> The fatigue strength is largely determined by surface properties, such as roughness, grain size, cold strain hardening and compression residual stresses. In order to increase the fatigue strength, therefore, the surface is frequently subjected to hardening by means of mechanical processes. In this connection, it is interesting to examine the question, to what extent the fatigue strength of surface hardened test specimens alters under cyclic stresses at high temperatures. In the case of valve springs made from oil quenched and tempered steel wire, it could be demonstrated that the fatigue strength is considerably improved at room temperature by shot peening, but that this improvement had totally disappeared at 250°C.

It might be assumed that if strain hardened specimens are tested at a temperature sufficiently high that recrystallization takes place, the material would recrystallize and thereafter assume properties similar to material which was annealed prior to testing. In this case, those specimens tested at a high stress, so as to cause failure in a short period of time, before recrystallization is completed, should show a greater fatigue strength than an annealed specimen. The S-N curve for the strain hardened material should start above the curve for the annealed material and at some point, where recrystallization is complete, it should merge with the curve for the annealed material.

In the experiment referred to by Wever, the effect of strain hardening had totally disappeared at 250°C. This is considerably below the temperature at which recrystallization would take place and thus shows that there are other phenomena involved.

In the study reported here, an attempt has been made to determine to what extent the increase in fatigue strength obtained by cold rolling is altered by cyclic stresses at elevated temperature. A type 430, high

chromium, low carbon stainless steel was selected for this investigation. This material, for the lower carbon contents, is generally a ferritic, non - hardenable alloy and was chosen because it should remain in the ferritic condition and thus would be free from complicating phase changes regardless of the temperature used. This steel can be effectively hardened only by cold working. A chemical analysis of the material used is given in Table 4-1.

The investigation was divided into three phases: (1) A series of recrystallization studies to determine first, a temperature at which no recrystallization would take place and second, a temperature at which recrystallization would be completed during the period of testing; (2) Design and construction of a high temperature fatigue testing apparatus; (3) A series of fatigue tests.

As a result of the first phase, temperatures of 1000°F and 1175°F were selected. Recrystallization curves for these temperatures are included in section two. The equipment used is described in detail in section three.

In the third phase, four series of tests were conducted, using a work hardened and an annealed material at each of the two temperatures.

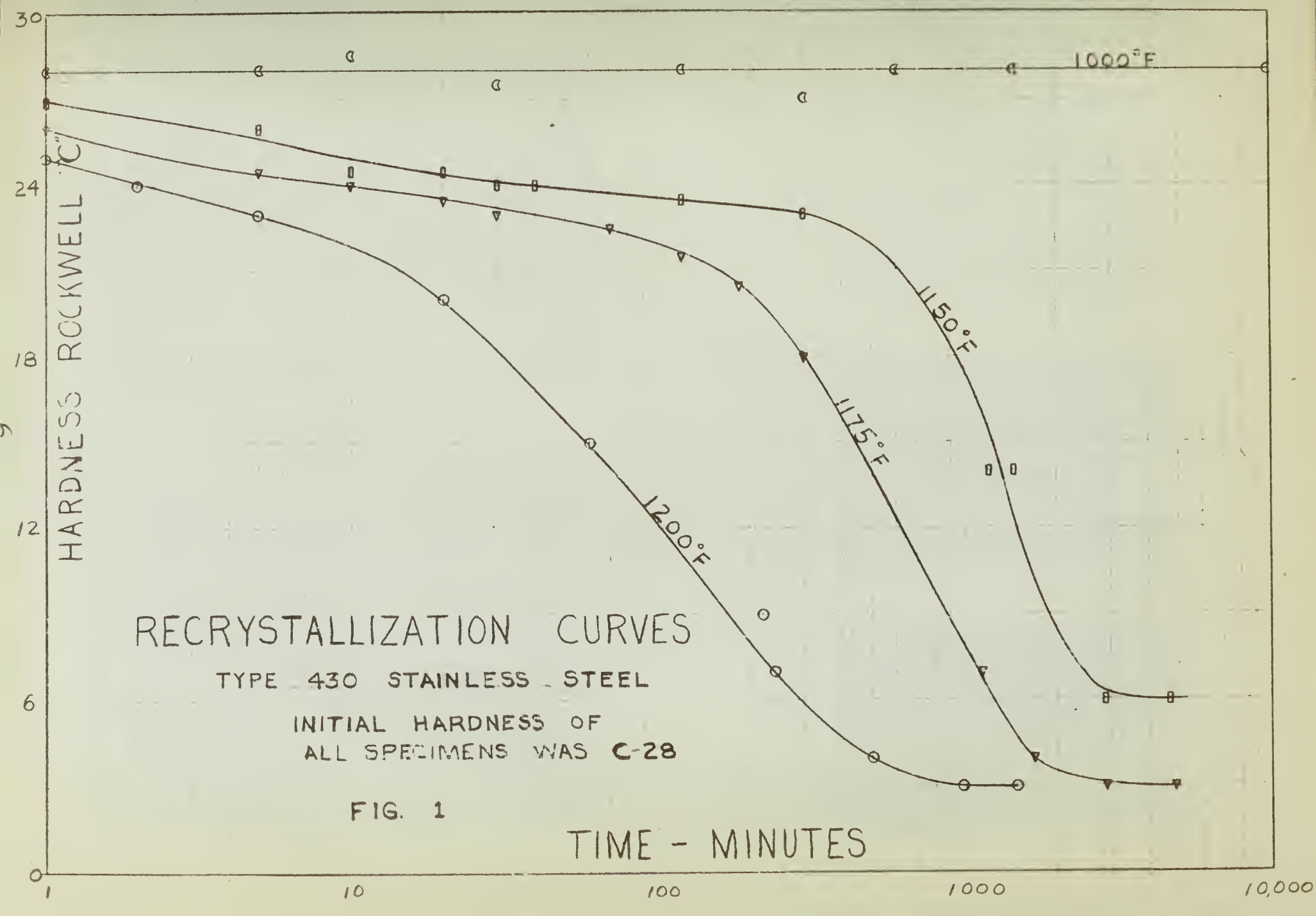
The experimental procedure used and the results obtained are described later.

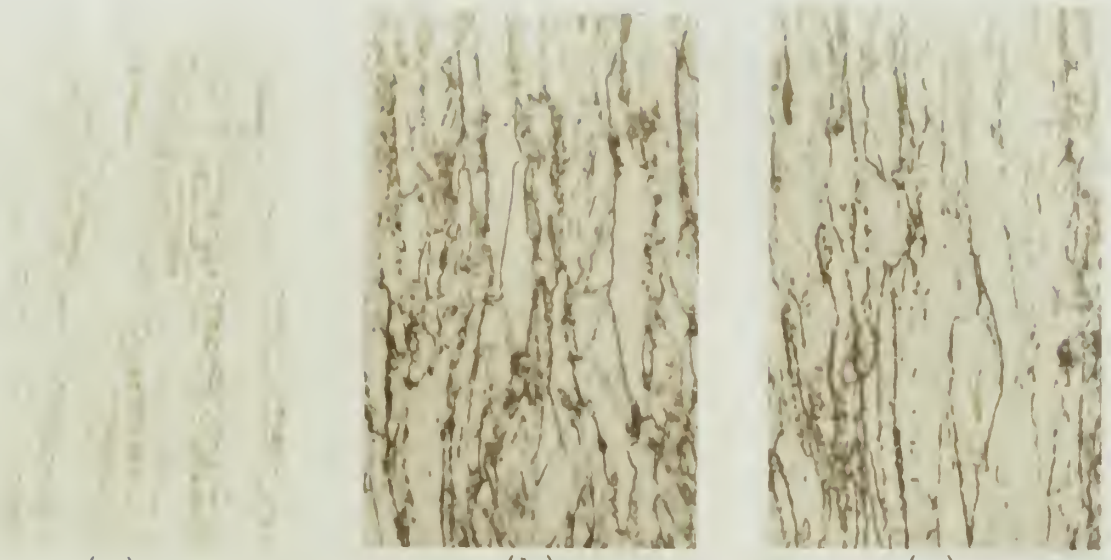
2. Recrystallization.

It was determined that with the equipment used, a specimen could be placed in a cold furnace and a period of two hours would be required for the furnace and specimen to reach equilibrium at 1200°F. With this as a starting point, a number of specimens were placed in salt baths at temperatures from 800°F to 1200°F and allowed to remain for two hours each. The Rockwell C hardness of these specimens was then plotted versus the temperature. From this curve, it was apparent that no recrystallization would take place at temperatures less than about 1050°F, within a two hour period. Appreciable softening took place within two hours only at temperatures above 1175°F.

Complete curves of hardness vs. time at temperature for several temperatures were then obtained and are shown in Figure 1. It will be noted from these curves, that at 1175°F, some softening does take place in the first two hours. Most of this takes place in the first two minutes and is attributed to a precipitation of carbides rather than to actual recrystallization. Photomicrographs of the structure substantiating this assumption are shown in Figure 2. It may be further noted that no recrystallization takes place at 1000°F within 7 days.

It was considered that if recrystallization was primarily responsible for the loss in improved strength due to strain hardening, then at 1000°F there should remain considerable improvement over annealed specimens at the same temperature. If as in the case referred to by Wever, some other phenomenon was responsible, the loss would probably be apparent at 1000°F. For this reason, 1000°F was selected as the temperature for the first set of tests. For reasons which will become apparent the second set of tests was conducted at a higher temperature.

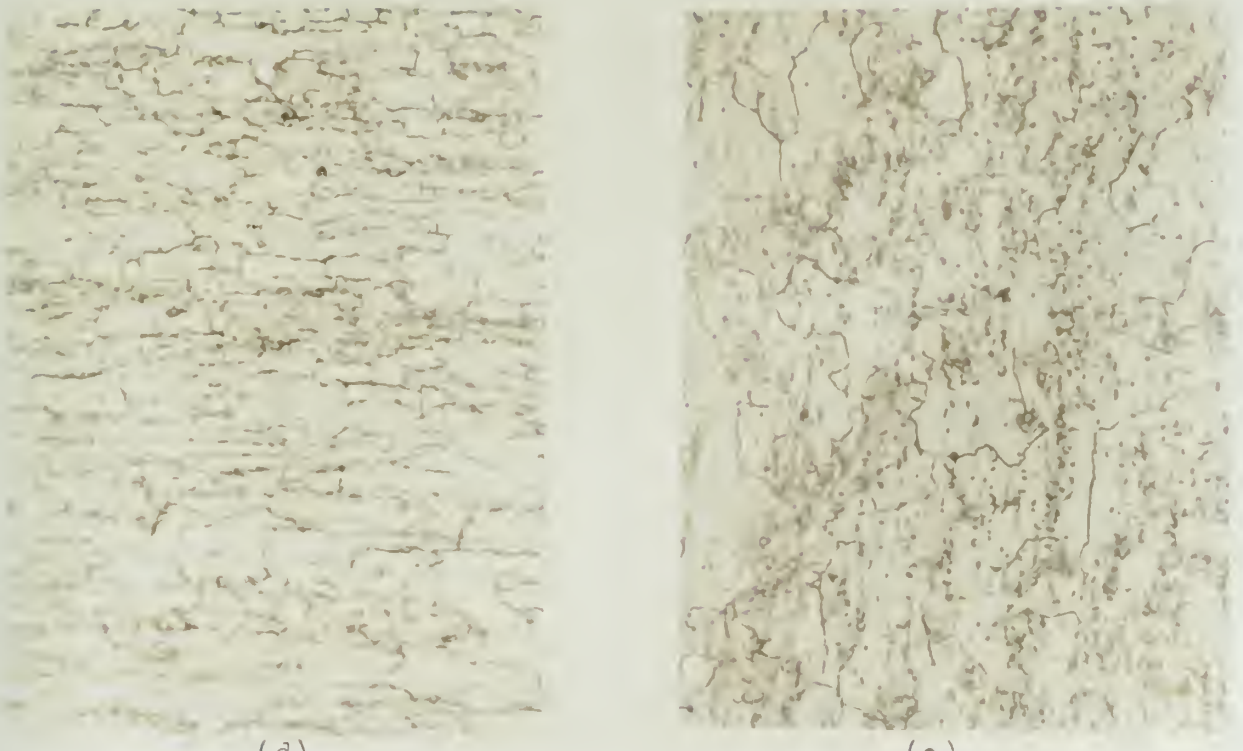

30
24
18
12
6
0
HARDNESS ROCKWELL "C"
1000°F
1150°F
1175°F
1200°F
RECRYSTALLIZATION CURVES
TYPE 430 STAINLESS STEEL
INITIAL HARDNESS OF
ALL SPECIMENS WAS C-28
FIG. 1
TIME - MINUTES
1
10
100
1000
10,000



(a)
As rolled

(b)
Annealed five minutes at 1175°F

(c)
Annealed one hour at 1175°F



(d)
Annealed 30 hours at 1175°F

(e)
Annealed two hours at 1500°F

Fig. (2)

3. Equipment.

Since there was no high temperature fatigue testing equipment available, it was found necessary to modify an existing fatigue testing machine. After a survey of the machines available it was decided to use two Sonntag Flexure Fatigue Machines (Model SF-2).[1] These machines were particularly well suited for this work, because they are of the constant repeated force type as opposed to the constant amplitude of deflection type. This made it unnecessary to know the modulus of elasticity of the specimen material in order to compute the applied stress. Since the modulus of elasticity is well known to vary with temperature and has been found by other investigators to vary with the number of cycles of alternating stress, it was deemed desirable to eliminate this quantity from the necessary calculations.

The Sonntag machine depends on an eccentric mass rotating at 1800 RPM to apply a preselected force to one end of a flat specimen loaded as a cantilever beam. The magnitude of the applied force is varied by changing the eccentricity of the mass. In order to keep the force applied to the specimen a constant irrespective of the amplitude of deflection, a system of inertia compensation is used. The function of this is to absorb all inertia forces in the vibrating system so that the eccentric force alone acts on the specimen.

The mechanical system employed in the Sonntag machine may be represented schematically by the system shown in Figure 3. In this system, K represents the spring constant of the tapered drive shaft of

1. Serial numbers of the machines used were: machine no. 1, 482451-4; machine no. 2, 482451-2.

the machine; k, is the spring constant of the specimen; M, is the mass of the vibrating system; m, is the mass of the eccentric weight, X, is the amplitude of deflection and w is the angular velocity of the rotating mass. The eccentricity of the rotating mass is e.

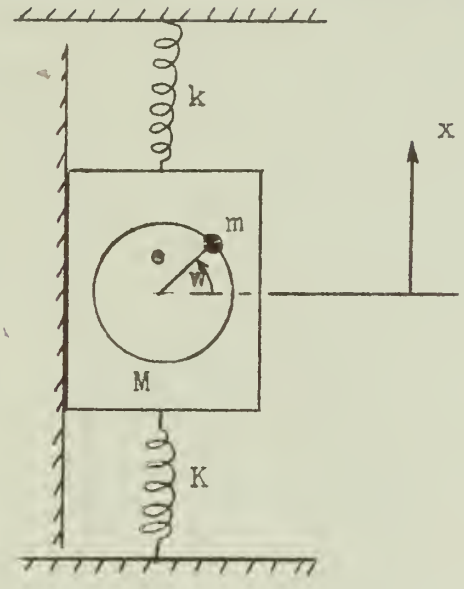


Figure 3

The differential equation describing this system is:

$$M\ddot{x} = -Kx - kx + mew^2 \sin wt \qquad (3.1)$$

A solution to this equation is $x = x_0 \sin wt$, and substitution of this solution gives:

$$(K - Mw^2)x_0 + kx_0 = mew^2 \qquad (3.2)$$

Since $mew^2 = P_0$, the force applied by the eccentric mass, and kx_0 is the force applied to the specimen, proper operation of the machine requires

that $P_0 = kx_0$ in which case:

$$K/M = w^2$$

In this condition, the machine is said to be tuned. Tuning of the machine is accomplished by moving the adjustable poise weights provided, in or out, thus changing M, the mass of the system.

When there is no specimen in the machine, $k = 0$ and if we let the ratio $K/M = w_n^2$ where w_n is the natural frequency of the system, we have from equation 3.2:

$$x_0 = \frac{P_0/K}{1 - (w/w_n)^2}$$

Therefore $$x = \frac{P_0/K}{1 - (w/w_n)^2} \sin wt;$$ from which it can be seen that as $(w/w_n)^2 \longrightarrow 1$, $x_{max} \longrightarrow \infty$. Since, as previously stated, the tuned condition of the machine results when $w_n^2 = w^2$, this fact can be used to tune the machine.

In modifying the machine for high temperature use, it was necessary to support the specimen at a height approximately two inches greater than in the original machine, in order to provide clearance for a furnace with adequate insulation. It was further required that the original aluminum specimen holding devices and the connecting push rod be replaced with parts made of stainless steel, which could withstand the furnace temperature. The addition of the new parts which were longer and of heavier material, acted to increase the mass of the vibrating system (M, in the above equations). It was found that this mass could not be

increased appreciably while still maintaining the ability to tune the machine with the poise weights provided. It was therefore necessary to design the modified parts so as to obtain approximately the same weight as in the original system. This was done by decreasing the diameter of the push rod from 5/16" to 1/4" and by making the front specimen holding bracket smaller.

All of the modified specimen holding devices were made of type 18-8 stainless steel with the exception of the large block which supported the rear specimen holding bar, (see Figure 4) and the bushings which served as bearings for the front holding bracket. The large block was made of mild steel because it was less expensive and much easier to machine, and this part was not subjected to extreme temperatures. The bushings provided a major problem in modifying the machine. In the original installation there were two small needle bearings in the front bracket. These supported a steel rod which was attached to the front end of the specimen, thus permitting a vertical force to be applied to that end without applying a moment. No bearings were available which could withstand the furnace temperature and it was decided to use bushings lubricated with powdered graphite as a substitute. An 18-8 journal rod was used and bushings made of bronze, Inconel, stainless steel, Lavite, and cast iron were tried. Of these, the first three were completely unsatisfactory. The Lavite, which is a ceramic material, easily machined in its raw state and extremely hard after proper baking, seemed at first to be ideal. When the journal was new and highly polished, the Lavite bushings were very satisfactory. After a time at temperature, the journal oxidized and became slightly pitted. This exerted an abrasive action on

the bushings and they were found to rapidly wear away under this treatment. The cast iron bushings were found to be the most satisfactory and these were used.

The modified machine was tuned by carefully adjusting the poise weights while the machine was running with no specimen and with P_0 set at a small value (0.5 lbs). The point of reasonance was easily found due to the very sharp increase in the amplitude of vibration at resonance. The correction for the effective weight of the specimen was made in accordance with the manufacturer's instruction book. (7)

The point of zero applied force was determined by mounting a microscope so as to observe a fine line scribed on the specimen holding bracket. A specimen was placed in the machine and the eccentric weight was adjusted so as to give a minimum deflection to the scribed line. The magnitude of this minimum deflection could not be measured accurately, however it was estimated to be slightly less than .001 inches. This would correspond to an applied force of about 0.15 pounds and an error in the computed stress of about 400 psi. This is considered to be the limit of accuracy of the equipment used. The graduated load scales of the machines were set so that the zero point corresponded with the minimum deflection point as determined above.

In order to verify that the machines were properly adjusted, one specimen was prepared with two electrical resistance strain gages mounted on it. The output from these gages was exhibited on an oscilloscope using an Ellis BA-1 bridge and amplifier. The applied load was computed from the measured strain using a tabulated value for the modulus of elasticity. The results

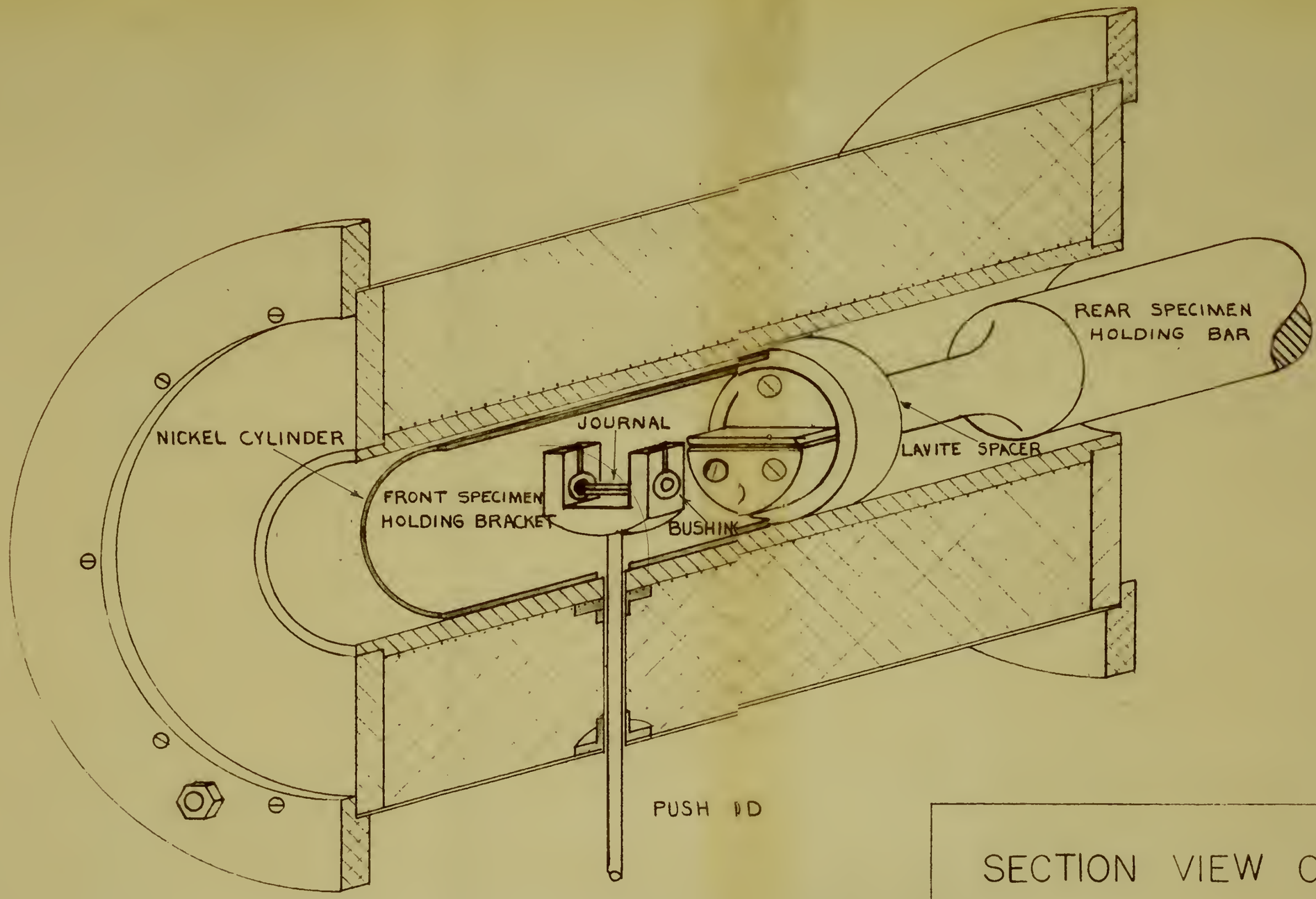
of this test indicated that the machines were properly tuned.

In order to obtain data at elevated temperatures, it was necessary to build and install a furnace with its associated power and temperature control equipment.

The furnace consisted of a ceramic tube 13-5/8 inches long by three inches inside diameter. Around this tube were wound 48 feet of 14-gauge Nichrome wire with the turns spaced 0.25 inches apart except in a one-inch section where the push rod of the machine penetrated the furnace wall. In this section, the turns were crowded to 0.125 inches apart to provide space for the push rod and to provide additional heat at a point where the push rod would act to conduct heat out of the furnace. There was some concern at this point that the eight-inch by 0.25-inch diameter push rod would become hot enough at its outer end to damage the aluminum bearing housing with which it connected. However, it was found that the low thermal conductivity of the stainless steel permitted the push rod to be maintained at 1000°F inside the furnace while its outer end was at a temperature of less than 120°F.

The outer shell of the furnace was made of 14-gauge aluminum sheet rolled into a tube 8-5/8 inches in diameter. The end plates were of one half inch Masonite board with aluminum rings around the outside to provide strength. The furnace was so mounted that it did not touch the machine at any point and therefore was not subjected to vibration. Details of the furnace construction are shown in Figure 5.

A 12-gauge nickel cylinder 2.9 inches in diameter and six inches long was placed inside the furnace core surrounding the specimen to aid in obtaining uniformity of temperature. Radiation shields were installed at



SECTION VIEW OF FURNACE

SCALE $\frac{1}{2}$" = 1"

FIG. 5

each end of the furnace for the same purpose.

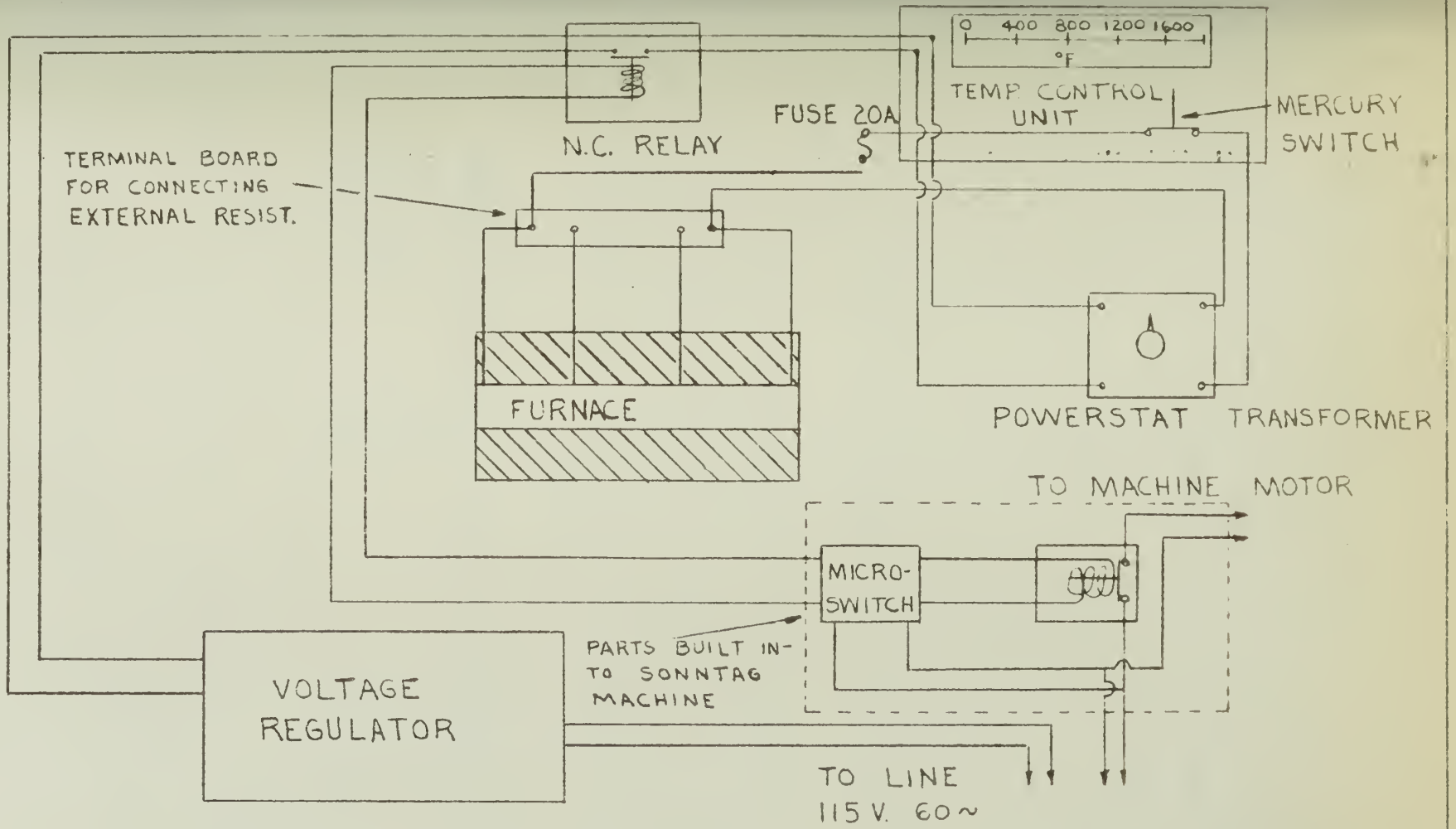
The furnace winding was made in three sections, so that external variable resistors could be placed in parallel with each section. This was done to provide a means of controlling the heat distribution along the specimen length, however, it was later found to be unnecessary. The specimen temperature could be maintained uniform without the use of the external resistors.

The total resistance of the furnace winding was 7.25 ohms and the input current was maintained at 10 amps, when the temperature desired was 1000°F. Temperature control was provided by a Minneapolis - Honeywell Pulse Pyr-O-Vane type temperature controller. This controller was actuated by a chromel-alumel thermocouple, the junction of which was placed on the outside of the furnace core opposite the center of the specimen. The controller contained a mercury switch which was either open or closed depending on the difference between the temperature indicated by the control thermocouple and that set manually on the instrument. This mercury switch controlled the output of a Powerstat variable auto transformer which supplied the input to the furnace winding. The current to the winding could be varied by varying the output voltage of the powerstat.

Due to the unreliability of the line voltage supplying the input to the powerstat, it was found necessary to provide a 2 KVA Sorenson & Company voltage regulator for supply voltage to the powerstat. The output of this voltage regulator was maintained constant at 115 volts.

The Sonntag machines are equipped with a microswitch which operates to turn the machine off when a specimen fails. This microswitch was

used to also open a normally closed relay in the furnace supply line and thus interrupt the power to the furnace when a specimen failed. Furnace power could be restored without restarting the machine, by turning the machine off and resetting the microswitch. The electrical circuit for the system is shown in Figure 6.



N.C. = NORMALLY CLOSED

SCHEMATIC DIAGRAM OF ELECTRICAL CIRCUIT FOR ONE FURNACE

FIG. 6

4. Design and preparation of specimens.

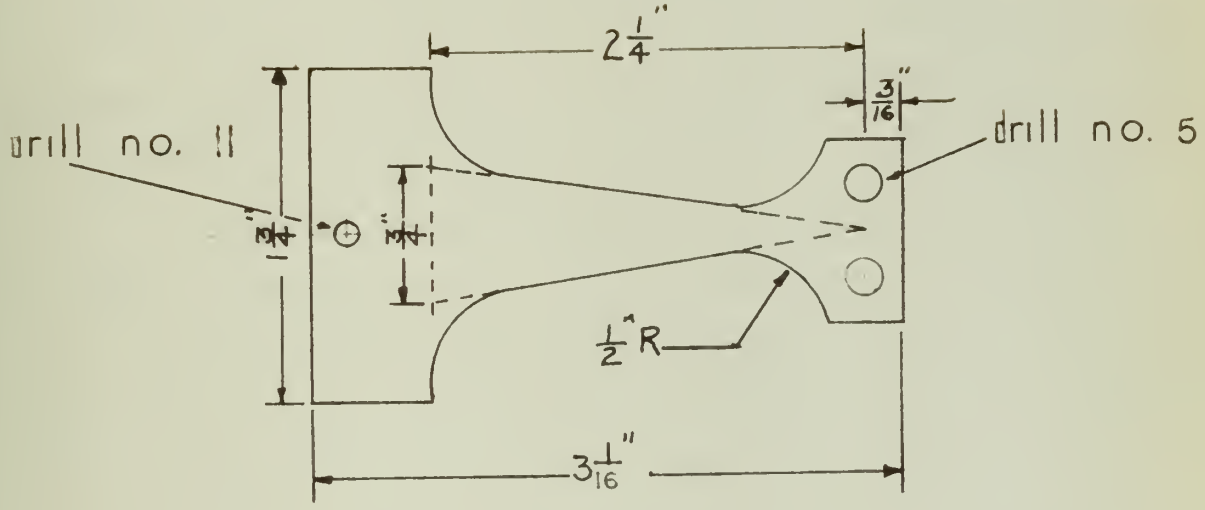
The details of the specimen design are shown in Figure 7. This design is a modification of the specimen design recommended by the Sonntag Scientific Corporation and designated "specimen No. 2" in the manufacturers instruction book (7). The modification consists of changes in the grip sections only and the stressed part of the specimen is identical with that recommended by the manufacturer of the machines. This type specimen is similar to the specimen known as the Bureau of Standards type and recommended by the American Society for Testing Materials (8). The grip sections were modified to effect more economy in the use of material.

Material for the specimens was procured commercially in the form of flat bars 1.75 X 0.1875 inches, in the hot rolled, annealed and pickeled condition. Chemical analysis as determined by courtesy of the Mare Island Naval Shipyard Industrial Laboratory is shown in Table 4-1.

TABLE 4-1

ELEMENT	WT.%	ELEMENT	WT. %
Carbon	0.080	Silicon	0.320
Manganese	0.490	Chromium	16.740
Phosphorous	0.020	Nickel	0.200
Sulphur	0.014	Molybdenum	0.080

It was necessary to roll the material to a thickness of 0.085 inches before cutting out specimens. This amounted to a reduction of 54.7% and is the condition used for the cold rolled specimens. The annealed condition was obtained by heating the specimens to 1500°F for two hours after they had been cut to the required shape.



SPECIMEN DESIGN

scale - full

FIG. 7

Following the rolling operation, specimen blanks were machined to the proper length and width and then were cut roughly to shape on a "Do-All" saw. Finish cutting was accomplished by using a "Tensil-Cut" machine and a template provided by the manufacturer of the machine. The tolerance allowed on the finish cutting was plus or minus 0.010". The error introduced by this tolerance is discussed later.

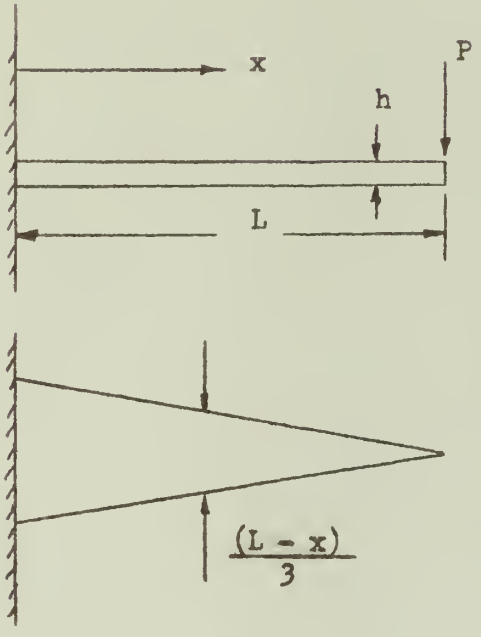
Following the machining operation, each specimen was polished by hand, using successively finer grades of metallographic paper and finishing with No. 000 paper. The finish obtained was estimated as a microfinish of from four to six by using standard microfinish specimens for comparison. It is conceded that a better finish might have been obtained, but it was considered that uniformity among specimens was more important and this was the objective in the polishing operation. All polishing, as well as the rolling, was in the direction of the longitudinal axis of the specimen. The time required to make and polish each specimen was about two hours.

Since it was not possible to predict the thickness of scale which would result from the annealing treatment, the thickness of finished specimens was not uniform. The actual thickness varied from 0.0766 to 0.0853 inches. In computing the applied stress, the actual thickness as measured by micrometer to 0.0001 inches was used. It is considered that any "size effect" resulting from this variation in thickness was negligible.

The stress applied was calculated from the applied force using the formula from strength of materials:

$$S = \frac{Mc}{I} \qquad \text{where:} \quad M = P(L-x); \quad c = \frac{h}{2}$$

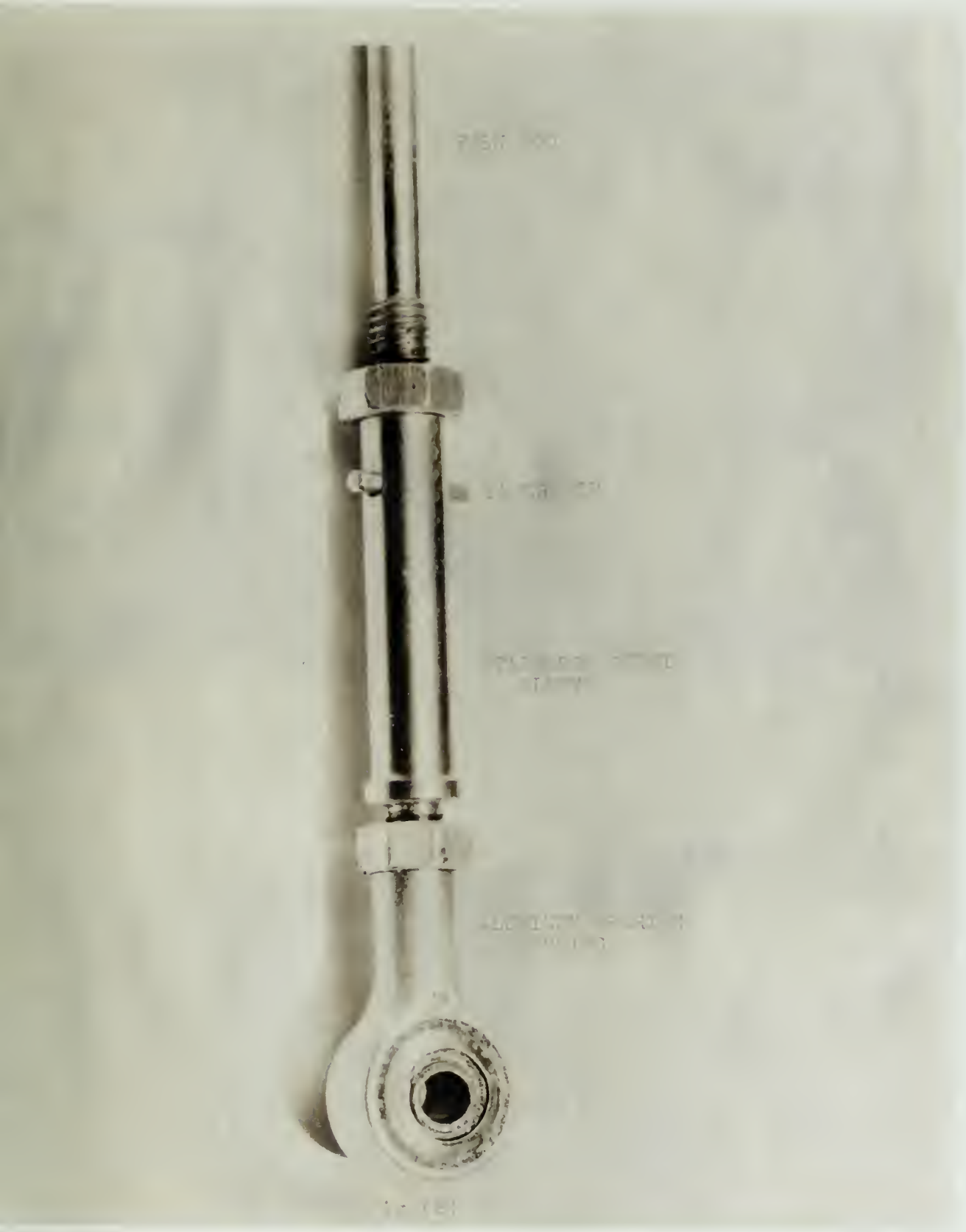
$$S = \frac{18P}{h^2} \qquad I = \frac{(L-x)h^3}{(3)(12)}$$

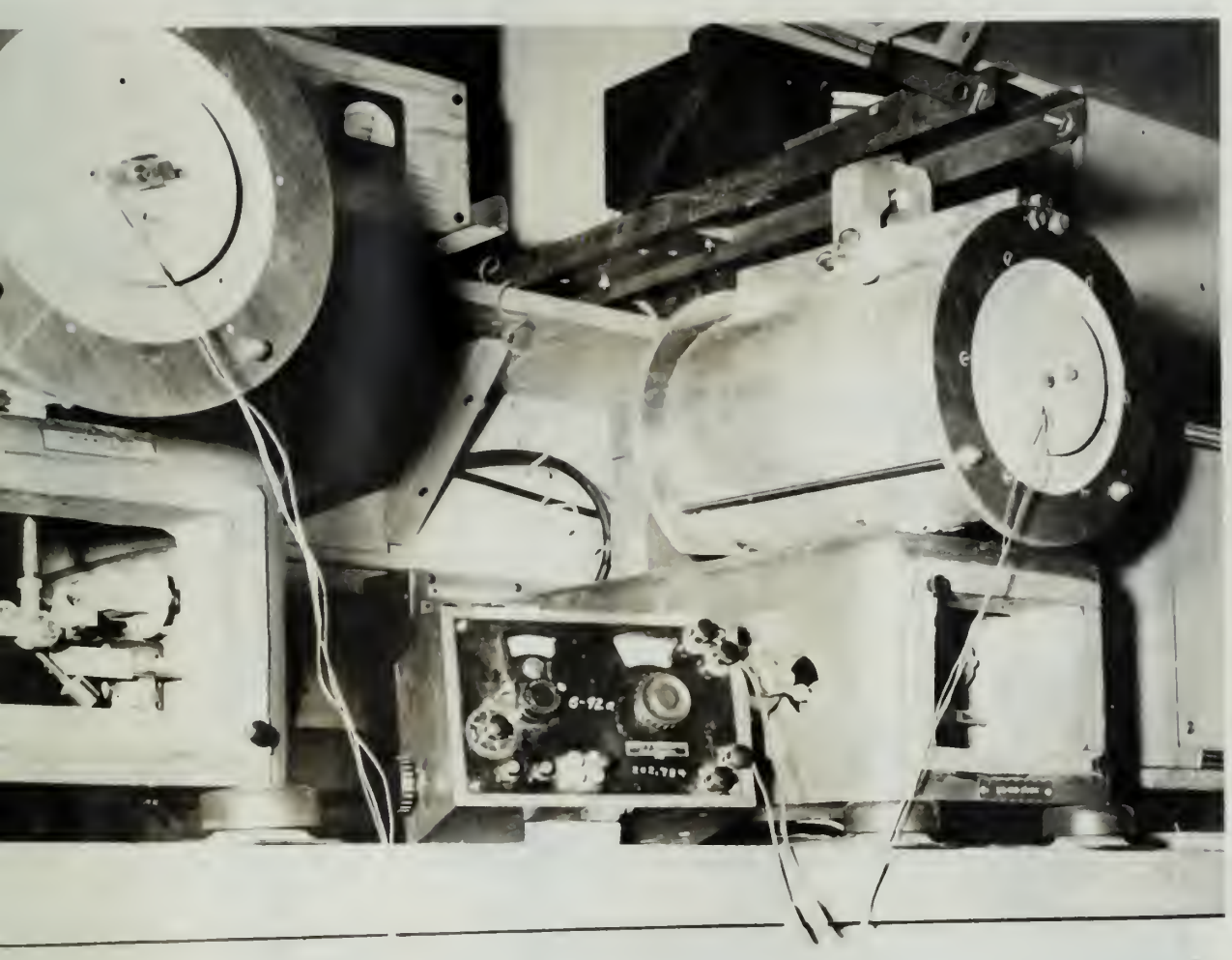


5. Experimental procedure.

The machines were set up and tuned as described in section three and the specimens were prepared as in section four. The furnaces were mounted on a track above the machines, in such manner that the furnace could be moved out on the track to reveal the specimen and holding devices. Before the furnace could be moved, however, it was necessary to remove the push rod. This rod was threaded into the front specimen holding bracket and connected at the opposite end to the aluminum bearing housing by means of a slip connection and a taper pin. (See Figure 8.)

In preparing for a test, the push rod was removed, and the furnace was moved out on the track. The specimen was then clamped in place, the thermocouples were attached, and finally, the furnace and push rod were replaced. The adjustment of the furnace at this point was extremely critical due to the small clearance provided for the push rod to enter the furnace. The push rod could not be allowed to touch the furnace because the resulting friction would decrease the applied force. Some difficulty was experienced in maintaining this alignment but the problem was solved as follows: A system of adjusting screws was placed on the furnace mounting plate. This permitted the furnace to be moved small distances in any direction. A thin walled stainless steel tube was used as a liner for the hole where the push rod entered the furnace and an electrical lead was connected to the outside of this tube. Another lead was connected to the rear specimen holding bar, and these two leads were connected through a dry cell battery to a flashlight bulb. Whenever the push rod was in contact with the steel tube, the light would be on and it was only necessary to adjust the screws to turn the light off, to ensure that





there was no contact between the furnace and the machine. This system eliminated much of the difficulty in aligning the furnace.

Three thermocouples were mounted in the furnace so that the junction points were in contact with the specimen at three equidistant points along the length. In the early stages of the project, the thermocouples were tied to the specimen using glass string, however, experience indicated that temperature measurement was just as good if the thermocouples were mounted in the furnace with the junction points against the specimen. An additional thermocouple was placed near the center of the specimen, and led out to a temperature recorder. This was only used periodically to maintain a check on the thermal characteristics of the furnace. Temperature control with the system used was considered to be excellent. After the two hour warmup period, the temperature gradient along the specimen was not more than three degrees Farenheit and the variation from the desired temperature was less than $\pm$ three degrees Farenheit.

There was a difference in the characteristics of the two furnaces in the manner of coming up to the preset temperature. The furnace designated number two heated faster than number one. In order to keep the temperature variation with time equal during the warmup period, it was necessary to increase the current to the number one furnace to 12 amps during the warmup period. When the desired temperature had been reached, both furnaces were operated at 10 amps. In every case, the furnaces were allowed to cool before changing specimens in order that the specimens would be exposed to the same treatment in each test.

With the specimen in the furnace and the temperature at the desired level, the load was set to give the desired stress and the machine was

started. The number of cycles to failure was determined by means of the electric revolution counter built into the machine.

In every case, there was a slight temperature rise when the machine was started. This was of the order of two or three degrees Farenheit and was attributed to the heat evolved due to plastic deformation. No correction was made for this temperature rise other than the eventual correction made by the temperature controller. Just prior to failure, there was a marked increase in the temperature due to the greater amount of plastic deformation occurring at this point. This was of the order of 15 to 20°F, but is considered to have no effect on the results, since the specimen had, for all practical purposes, already failed at this point.

In any study of fatigue, it must be expected that the results will show large amounts of scatter. This may result from variability in selection of material, in preparation of specimens, in test conditions and/or in measurements. In addition to these factors over which the experimenter may have some control, there may be other factors which are beyond the control of the experimenter. Scatter is not peculiar to fatigue testing, but may be noted in any tests of mechanical properties of materials. The important difference is that, in fatigue, the amount of scatter is generally larger.

To obtain quantitative results, the present trend in fatigue testing is to conduct a large number of tests for each condition for which an S-N curve is to be obtained. Several hundred tests may be required to accurately establish each curve. Methods of statistical analysis are then applied to the data to obtain the S-N curve.

The ASTM Manual on Fatigue Testing (8) suggests that at least ten

specimens be tested for each S-N curve when attempting to obtain qualitative results. In the work of Toolin and Mochel (9), which has become a classic in the field of high temperature fatigue, from five to ten specimens were tested to establish each S-N curve. In more recent studies by the Air Materiel Command (10), four to eight specimens were used for each curve. The Bureau of Aeronautics of the U. S. Navy, at the Naval Air Materiel Center, Philadelphia, has been using 12 specimens to establish each S-N curve. (11)

These reports indicate that much work is being done in obtaining qualitative rather than quantitative data in high temperature fatigue testing.

In the study reported here, it was realized that it was not feasible to conduct the necessary tests to obtain quantitative results. It was decided to test 15 specimens in each set in an attempt to obtain general trends only.

In the first series of tests, conducted at 1000°F, using cold rolled material, 20 specimens were tested. Because of the greater amount of scatter obtained on this run, more specimens were deemed necessary in order to locate the S-N curve. A number of problems were encountered in this part of the investigation, which may have contributed to the scatter. Among these were those associated with temperature control and specimen preparation. It was found that the line voltage was subject to considerable fluctuation; particularly during the night when the building was unoccupied. In general, the tendency was for the voltage to rise above the normal level, which would cause the temperature to rise. The temperature controller was of a type which was dependent on a steady input voltage

for precise temperature control. A large rise in voltage caused excessive current to flow, overloading the 12 amp fuses originally used, and thus ruined the test in progress.

The preparation and polishing of specimens was a laborious project and several methods were tried in order to develop a satisfactory technique. Because of this, there may have been some slight variation in the surface finish of the specimens of the first set. The cold rolled material is known to be more notch sensitive than the annealed, and therefore, would be more sensitive to variations in surface finish. It is believed that this variation in surface finish is largely responsible for the increased scatter in the data taken from the first set of specimens. The variation in temperature is discounted as a cause, since when occurring, this was sufficient to consider the test invalid. A total of 28 specimens was tested in this set, of which, eight were discarded due to temperature variations. While conducting the first set of tests, a standard technique for polishing specimens was established and voltage regulators were installed to correct the problems mentioned.

Other possible sources of error in results were as follows:

a. Errors in machining of specimens. A tolerance of 0.010 inches was allowed in the machining of specimens. In most cases the actual error was about one half the allowed error. The error in stress caused by this machining tolerance is plotted in Figure 11. From this, it can be seen that an error of 0.010 inches caused a variable error in stress ranging from about 1.5 to 5% along the gage length of the specimen.

b. Local stresses introduced by clamping the specimens in the machine. It is considered that the grip section of the specimens was

sufficiently large, that the effect of these stresses in the stressed part of the specimen was negligible.

c. Temperature errors. These are considered negligible in all cases where the test was considered valid. Accuracy of temperature control was discussed in section three.

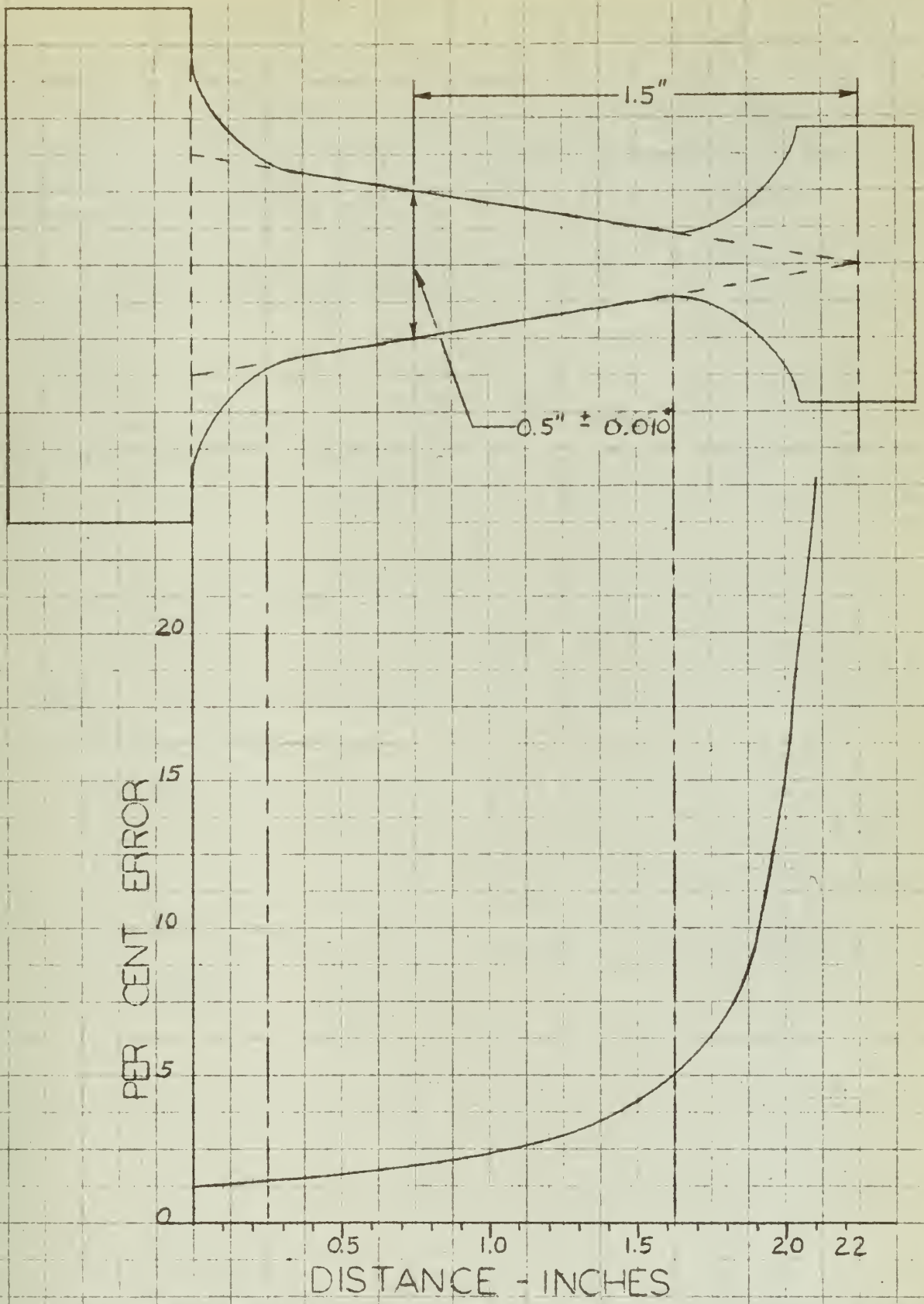
d. Errors in measurement of thickness of specimens and in computation of applied stress.

e. Errors in setting of desired load on machine. With the system used, parallax made it easy to make an error of one half pound in setting the load. Care had to be used to avoid this.

f. Errors inherent in the machine. These were discussed in section three.

g. Variation in surface finish of specimens. The major source of error involved in this was the varying amount of material removed from each specimen in the polishing operation. The actual surface finishes obtained were relatively uniform, however, there is some uncertainty as to the variation in the amount of residual stress removed from the specimens by polishing.

h. Errors in the number of cycles to failure. The counter only recorded to the neartest 1000 cycles. Except at the very high stresses, an error of 1000 cycles is negligible.



ERROR IN COMPUTED STRESS RESULTING FROM 0.010" ERROR IN MACHINING OF SPECIMENS

FIG. 11

6. Presentation of results.

In this investigation, a total of 65 specimens was tested. The results of these tests are shown in Figure 12, and the data for these curves are included in Appendix I.

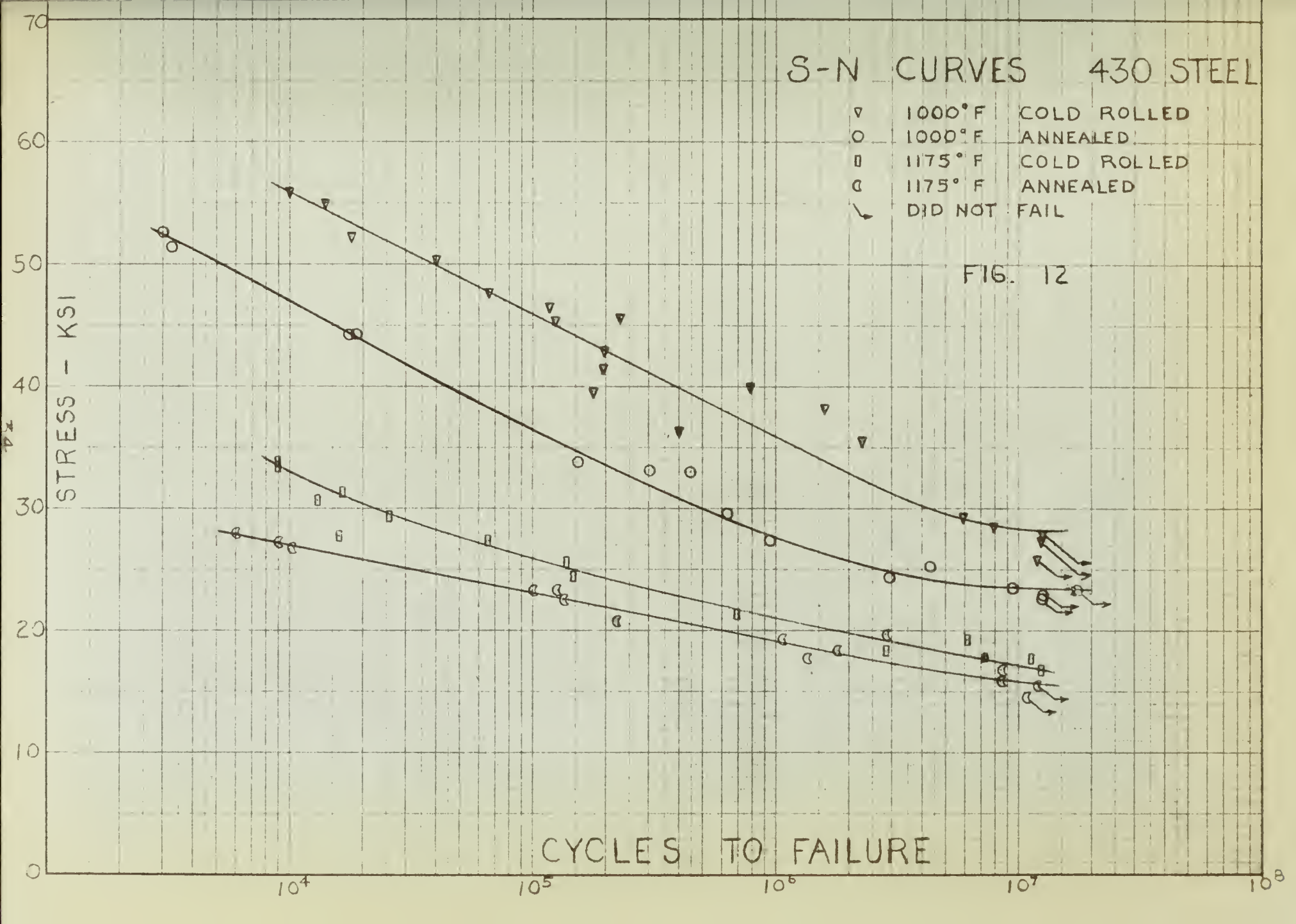
At 1000°F, the fatigue strength, at ten million cycles, of the cold rolled material is approximately 25% greater than that of the annealed specimens.

When the temperature is raised to 1175°F, the fatigue strength at ten million cycles is practically the same in each case. The strength at this temperature is considerably less than that obtained on either of the 1000°F runs.

At the higher stress levels, where the fatigue life is shorter, the cold rolled material shows a greater improvement at both temperatures. However, at the higher temperatures, this improvement rapidly diminishes with increasing fatigue life.

The scatter obtained on these tests is normal for this type of work. (1)

In every case, the fractures obtained were transgranular in nature. A photomicrograph of a typical crack in a specimen from each run is shown in Figure 13. The numbers in this figure refer to the specimen numbers as shown in appendix 1.


S-N CURVES 430 STEEL
▽ 1000°F COLD ROLLED
○ 1000°F ANNEALED
▯ 1175°F COLD ROLLED
◐ 1175°F ANNEALED
↘ DID NOT FAIL
FIG. 12
STRESS - KSI
CYCLES TO FAILURE
0
10
20
30
40
50
60
70
10^4
10^5
10^6
10^7
10^8

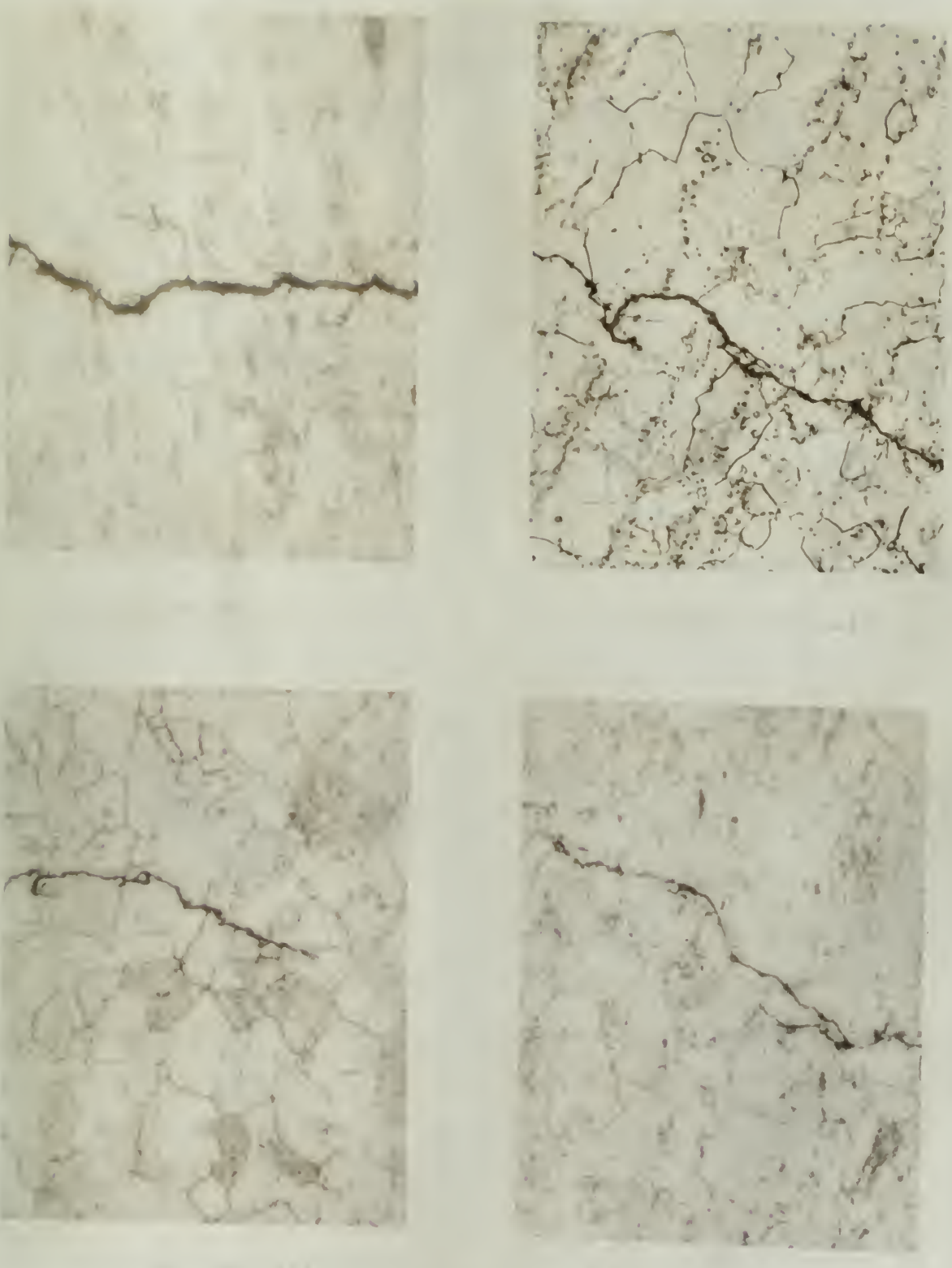


Fig. (13)

Photomicrographs showing a typical fracture from each run. (500 X)

7. Discussion.

In analyzing the results of a fatigue study, it is necessary to consider the mechanisms which cause fatigue. Although a number of theories have been proposed, the processes which take place are not well understood, and there is considerable disagreement among the authorities on this subject.

It is generally agreed that fatigue takes place in three stages. First minute cracks, which are sub-microscopic in size are formed. These then increase in number and coalesce to form larger cracks, which are propagated through the material with successive cycles of loading. As these cracks spread, the cross section of sound material is gradually reduced, thus weakening the part until it finally fails.

Probably the least understood and consequently the most controversial phase is that in which the initial cracks are formed. It has been estimated that from 50 to 90% of the fatigue life is expended during this phase, before the cracks reach microscopic size.

Most authorities agree that the conditions which cause the formation of these cracks exist in highly localized regions only. Since the mechanism of fatigue is quite complicated, various simplifying assumptions have been made in attempts to describe the process. The usual engineering assumption which pictures the material as a continuous, isotropic, homogeneous, elastic body, has been found inadequate for any theoretical approach to fatigue.

One of the more classic theories of fatigue is that of Orowan (12), in which he proposed a geometrical model to explain the fatigue mechanism.

Orowan's model consisted of a "plastic inhomogeneity" within elastic surroundings. This inhomogeneity could be either a fault in the ordinary metallurgical sense or merely a crystallite oriented unfavorably with respect to the applied stress, so that its yield point is exceeded by an applied load which produces only elastic strains in the surrounding material. Orowan considered the effect of repeated applications of load to the model. Successive plastic deformation under each cycle of stressing of the small region causes two effects: 1) Deformation which may be cumulative under succeeding cycles until a crack is formed, and 2) local strain hardening and corresponding stress relief which strengthens the region and shifts the stress maxima under succeeding cycles to adjacent portions.

By means of this theory and certain simplifying assumptions, Orowan was able to explain many of the observed phenomena of fatigue behavior.

Freudenthal (13) has discussed a process of crack formation based on the slip and crystal fragmentation which occur due to work hardening. In the loading part of each cycle, slip and crystal fragmentation occur, and these set up microresidual stresses during the unloading part of the cycle. Cracks form, at the points where these residual stresses are most intense, when the elastic energy locally stored during one cycle, can no longer be released by slip on subsequent cycles.

Machlin (14) among others, has suggested that the cracks are formed when local plastic deformation is caused by a piling up of dislocations at certain points in the material. Other theories making use of dislocations and voids have been proposed, however, these are not yet generally accepted. As more experimental data are obtained, it appears likely that these

theories will provide a better description of the phnenomena involved than the earlier theories.

Regardless of the mechanism by which the initial cracks are formed, there seems to be little doubt that fatigue is dependent on their formation. These cracks are submicroscopic in size and are caused by rupture of atomic bonds in cleavage. It is generally agreed that the formation and propagation of the cracks depends on continuously changing conditions at anypoint in the material. In a truly isotropic, homogeneous, elastic body, those bonds which resisted rupture on the first cycle of loading, would have no cause to break on subsequent cycles. If the requirement of an elastic material is eliminated, it would seem that slip would take place when the applied load was sufficient to cause yielding. Yet, it is known that fatigue can take place at stresses well below the yield point. Thus, the material cannot be homogeneous, but must contain certain regions where plastic deformation takes place at stresses below that necessary to cause yielding of the surrounding material.

Due to the necessity for conditions which are continuously changing, there must always be some plastic deformation, at least over a very small region, or there can be no fatigue.

In the process of cold rolling the material, compressive residual stresses are set up near the surfaces. In that part of the loading cycle in which tension is applied to the surface considered, these compressive stresses must be overcome before any tension is felt by the surface material. Therefore, a greater load may be applied before any plastic deformation occurs, than would be possible if these compressive stresses were not present.

If the magnitude of the applied load is so small that no slip occurs, there should be no new cracks forming after the first cycle of load. If a greater load is applied some slip may take place in highly localized regions. If this slip is contained in an elastic matrix, by which it is rapidly reduced in intensity and finally stopped, no progressive damage occurs. Some submicroscopic cracks might form in this case, but these would be isolated and relatively few in number. It is only when conditions are continuously changing that progressive crack formation and propagation can take place. Freudenthal states that the existence of an elastic matrix to contain localized plastic deformation, is the condition necessary for an endurance limit.

At elevated temperatures, the increased thermal motion makes the probability of slip and bond rupture greater. Less applied force is necessary to produce plastic deformation at a given point, and, for a given stress level, crack formation and propagation will proceed at a faster rate. Therefore, the fatigue strength should decrease with increasing temperature. This is known to be true from the results of this investigation and many others.

As the temperature approaches the recrystallization temperature, the application of any load will cause plastic deformation. It is possible that the slip which occurs on one cycle of load will be contained by elastic deformation of the surrounding material, (the condition necessary for the existence of an endurance limit). However, it is known that relaxation and recovery occur, and it may be that this permits further slip to occur in the same region on subsequent applications of the same stress level. This inability of the material to work harden could permit cumulative slip

which would eventually form a crack, and since the continuously changing conditions exist, the crack would be propagated through the material. Since the rate at which relaxation and recovery occur is dependent on the temperature, it would seem that the temperature at which an endurance limit no longer exists, would depend on the frequency of the alternating load.

At and above the recrystallization temperature, a specimen subjected to alternating stresses is in effect being hot worked. Recovery and recrystallization occur immediately and no work hardening is possible. At these temperatures, therefore, it would be reasonable to assume that plastic deformation could never be contained by an elastic matrix and no endurance limit could ever exist, regardless of the frequency of loading. At lower temperatures, relaxation and recovery are slower, thus for high frequency loading, it would be possible that the elastic stresses, caused by slip on one cycle of load, would not be relieved prior to the next application of load. In this case cumulative slip would probably not occur and it would be more likely that deformation would occur at another point. Therefore, an endurance limit could exist. At lower frequencies, there would be a greater probability that the elastic stresses would be relieved before the next application of load. This would permit cumulative slip to occur which would eventually lead to propagating cracks and finally fatigue failure. Therefore, no endurance limit would exist at the lower frequency.

There is much experimental evidence to show that the endurance limit for steels disappears above certain temperatures, however, there has been very little speculation as to the cause of this.

In the study reported here, 65 specimens were tested at temperatures

of 1000°F and 1175°F, in order to obtain the four S-N curves shown in Figure 12*. No tests were conducted at room temperature due to time limitations, however, it is generally agreed that at room temperature, the fatigue strength is proportional to the ultimate tensile strength. (1) For the material used, the ultimate tensile strength in the cold rolled condition, as determined by test, was 125,000 psi, and in the annealed condition it was 74,000 psi. Therefore, the process of cold rolling caused an increase in the room temperature tensile strength of 69%. It is assumed that the increase in the fatigue strength at room temperature is approximately the same.

Examination of the curves of Figure 12*, shows that a substantial improvement in the fatigue strength of the cold rolled material still exists at 1000°F. The improvement at this temperature is of the order of 25% in the fatigue strength at ten million cycles. This is much less than the estimated improvement available at room temperature and the decrease is attributed to a loss of the compressive residual stresses in the surface material. Hultgren (15) shows that residual stresses can be removed by annealing even at temperatures well below the recrystallization temperature. In this case, it is considered that while no softening has occurred and the material is still in the cold worked state containing shattered crystal lattices and many heterogeneous stresses, the homogeneous stresses produced by cold work have been largely relieved. The applied load necessary to produce plastic deformation, is still larger than that required for the annealed material at the same temperature. However, now there is no compressive stress to be overcome by the applied tensile stress.

When the temperature is raised to 1175°F, a definite improvement still

* See Page 34.

exists in the cold worked material at the higher stress levels. At a stress to cause failure in 10,000 cycles, the cold rolled material is approximately 30% stronger. As the stress level is decreased, the curve for the rolled material converges with that for the annealed material. With the scatter obtained in these tests, it is impossible to state that the two curves merge into one, but it appears that they tend to do so. A specimen which fails in 10,000 cycles, is only acted upon by the alternating load for about five minutes. In this time very little recrystallization takes place and the specimen is actually in the work hardened state until it fails. As the time to failure increases with decreasing stress, the specimens approach the fully recrystallized condition and thus become the same as the annealed specimens.

At 1000°F there appears to be a break in the curves, at about ten million cycles, which would indicate the existence of an endurance limit at this temperature. The curves obtained at the higher temperature are much flatter and do not contain such a break. This tends to confirm the theory previously discussed, however, there are not sufficient data available to justify positive conclusions concerning the existence or nonexistence of an endurance limit.

From the data obtained, it appears that the process of cold working the material produces an increase in the fatigue strength by two primary methods: 1) homogeneous residual stresses, which are compressive at the surfaces, are set up; and 2) due to the work hardened state of the crystal lattices, few atoms remain at the equilibrium distance from their neighbors, resulting in heterogeneous stresses throughout the material. The homogeneous residual stresses are largely annealed out at some temperature

below 1000°F whereas the heterogeneous stresses are primarily eliminated during recrystallization.

In the case of the shot peened springs referred to in section one, it would seem that the strengthening effect of shot peening is due almost entirely to the compressive residual stresses set up. Because of the very small volume of material plastically deformed in this process, the beneficial effect of the heterogeneous stresses would be small. Therefore, it could be expected that the improved strength of cold working would be almost completely lost upon the relieving of the homogeneous stresses.

A similar effect would probably be noted when shafts with cold rolled fillets are used at elevated temperatures.

There are a number of engineering applications which make use of residual stresses to prolong fatigue life. In gear teeth, for example, the process of case hardening the teeth sets up residual stresses at the tooth foot. If the case hardening is properly done, the fatigue strength of the tooth foot may be greatly improved. (16) Designers who make use of this principle in gears for high temperature use, must consider the temperature at which these residual stresses will be annealed out. There are also techniques for cutting threads which make use of residual stresses to improve the fatigue strength. These too, are subject to considerable loss in fatigue strength at elevated temperatures.

8. Conclusions and recommendations.

(a) Conclusions

As a result of these experiments, it has been shown that the improvement in fatigue strength, obtained by cold working, is retained at high temperatures to a sufficient degree to make this method worthy of consideration in engineering practice.

It has also been shown that when the recrystallization temperature is reached, the improvement due to cold work gradually disappears with time at temperature.

Sufficient tests were conducted to show that the equipment and methods developed are adequate for conducting high temperature fatigue tests.

(b) Recommendations

Due to the scarcity of high temperature fatigue data, it is recommended that further investigation be made.

It would be interesting to conduct a series of comparisons between cold worked and annealed material at various temperatures below the recrystallization temperature, to determine if there is a gradual loss of improved strength or if there is some elevated temperature range at which the improvement is rapidly lost.

It is also recommended that a series of studies be made, using materials with different recrystallization temperatures, to determine if the existence of an endurance limit is dependent on the recrystallization temperature.

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APPENDIX I

DATA FOR S - N CURVES

Run No. 1, Cold Worked, Hardness Rockwell C 28
Test temperature 1000°F

SPECIMEN NUMBER	LOAD IN POUNDS	MACH. NO.	THICKNESS INCHES	STRESS PSI	CYCLES TO FAILURE
1-1	20	1	0.0817	56,000	10,000
1-2	17	1	0.0822	46,700	118,000
1-3	13	1	0.0812	36,300	401,000
1-4	10.40	1	0.0850	25,820	12,000,000*
1-5	11.55	1	0.0853	29,250	5,906,000
1-6	14.14	1	0.0845	35,000	791,000
1-7	13.98	1	0.0844	35,700	2,292,000
1-8	11.50	1	0.0844	28,600	7,929,000
1-9	15.70	1	0.0840	39,600	477,000
1-10	16.70	1	0.0841	47,900	66,000
1-11	18.70	1	0.0843	50,300	40,000
1-12	17.92	1	0.0844	45,400	123,000
1-13	17.92	1	0.0842	45,600	227,000
1-14	15.00	1	0.0848	38,100	1,591,000
1-15	15.85	1	0.0843	41.600	196,000
1-16	15.35	1	0.0841	43,000	198,000
1-17	9.90	1	0.0798	28,000	12,338,000*
1-18	9.90	1	0.0810	27,200	12,346.000*
1-19	19.00	1	0.0810	52,100	18,000
1-20	20.00	1	0.0810	55,000	14,000

Run No. 2, Annealed at 1500°F for 2 hours, Hardness Rc 3
Test temperature 1000°F

2-1	11.50	1	0.0793	33,000	446,000
2-2	8.00	1	0.0782	23,600	9,403,000
2-3	8.00	1	0.0785	23,400	17,407,000*
2-4	11.40	2	0.0778	33,900	152,000
2-5	15.20	2	0.0786	44,250	18,900
2-6	10.80	2	0.0766	33,100	304,000
2-7	9.50	2	0.0790	27,400	942,000
2-8	18.00	2	0.0795	51,400	3,300
2-9	18.00	1	0.0784	52,800	3,000
2-10	8.50	1	0.0780	25,200	4,660,000
2-11	15.40	2	0.0793	44,200	17,800
2-12	10.00	2	0.0780	29,600	633,000
2-13	7.70	1	0.0782	22,700	12,300,000*
2-14	7.80	1	0.0781	23,000	12,560,000*
2-15	8.30	2	0.0785	24,300	2,980,000

Note: Eight specimens from run number one, and one specimen from run number two were discarded due to excess temperature variation. These were disregarded in numbering the remaining specimens.

* Did not fail

Run No. 3, Annealed at 1500°F for 2 hours, Hardness Rc 3
Test temperature 1175°F

SPECIMEN NUMBER	LOAD IN POUNDS	MACH. NO.	THICKNESS INCHES	STRESS PSI	CYCLES TO FAILURE
3-1	5.00	1	0.0785	14,620	10,068,000*
3-2	7.00	2	0.0796	19,800	2,854,800
3-3	9.60	2	0.0798	27,100	9.000
3-4	8.00	2	0.0789	23,200	126,800
3-5	8.00	2	0.0789	23,200	99,000
3-6	7.20	2	0.0788	20,800	220,000
3-7	6.70	2	0.0793	19,200	1,071,900
3-8	6.33	1	0.0800	17,820	1,305,000
3-9	6.50	2	0.0790	18,350	1,794,600
3-10	5.80	2	0.0786	16,900	8,536,600
3-11	5.60	1	0.0796	15,900	8,232,000
3-12	9.80	2	0.0794	28,000	6,000
3-13	7.80	1	0.0790	22,500	132,000
3-14	5.50	1	0.0800	15,500	12,000,000*
3-15	9.50	2	0.0798	26,800	10,000

Run No. 4, Cold worked, Hardness Rockwell C 28
Test temperature 1175°F.

4-1	7.00	1	0.0832	18,200	2,836,000
4-2	7.00	2	0.0839	17,950	11,324,700
4-3	11.00	1	0.0842	27,900	16,000
4-4	7.50	1	0.0841	19,100	6,093,000
4-5	9.50	2	0.0836	24,400	147,600
4-6	10.00	1	0.0840	25,600	137,000
4-7	11.50	1	0.0840	29,400	26,000
4-8	12.00	2	0.0831	31,300	16,400
4-9	13.00	2	0.0833	33,700	7,900
4-10	12.00	1	0.0840	30,700	13,000
4-11	13.00	2	0.0832	33,800	7,900
4-12	8.25	1	0.0835	21,300	692,000
4-13	10.00	2	0.0835	27,300	65,300
4-14	7.00	1	.0835	18,100	7,349,000
4-15	6.50	2	0.0831	16,950	12,240,000

* Did not fail